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DARPA) OPTOMECHANICAL LIGHT-MATTER INTERFACE WITH OPTICAL WAVELENGTH CONVERSION

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Final Technical Report

Optomechanical Light-Matter Interface with Optical Wavelength Conversion

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Abstract

An optomechanical resonator features the unique property that an optically active mechanical mode can couple to any of the optical resonances in the resonator via radiation pressure. The main objective of this program is to exploit this unique property to develop a light-matter interface that can map quantum states between two different optical wavelengths. Using silica microspheres as a model optomechanical system, these studies have led to the experimental realization of coherent inter-conversion between optical and mechanical excitations and to the demonstration of mechanically-mediated coherent conversion between two optical modes. In addition, Bogoliubov mechanical mode, which is a precursor for entangled mechanical mode, has also been realized in a system, in which two mechanical modes couple a common optical mode via respective red and blue sideband coupling.

A particular emphasis of this program is on overcoming the effects of the thermal mechanical motion in mechanically-mediated optical state transfer or optical entanglement. Two different approaches have been proposed and analyzed theoretically. One approach exploits mechanically-dark optical super modes. These dark modes can enable the optical mode conversion or optical entanglement generation without exciting the mechanical system, thus avoiding the effects of the thermal mechanical motion. Detailed experimental studies show that optical mode conversion demonstrated indeed took place via the dark mode. Another approach returns the mechanical system to its initial state after the completion of the relevant quantum operations. This approach resembles the Sorensen-Molmer mechanism for entanglement of trapped ions in a thermal environment. Both approaches aim to take advantage of mechanical degrees of freedom, while avoiding the detrimental effects of thermal mechanical motion.

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1. OVERVIEW

In a quantum network, local quantum nodes consisting of matter qubits generate, process, and store quantum information. An optical network couples together distant quantum nodes, transferring or distributing quantum information among these nodes via photons[1]. Such a network can play a major role in quantum communication and quantum computing and can also serve as a platform for exploring and understanding quantum manybody interactions. A variety of quantum systems including both atomic and solid state systems, such as trapped ions, superconducting circuits, and spins in diamond or silicon, have emerged as promising candidates for matter qubits. The unique properties of these quantum systems make them suitable for specific quantum operations. For example, spins in diamond can serve as long-lived quantum memories, while superconducting circuits can enable rapid information processing. A formidable challenge for developing a hybrid quantum network that can incorporate and take advantage of disparate quantum systems is to enable quantum communication between these systems.

An effective approach for mediating interactions between different types of quantum systems emerged from a seemingly unrelated field, cavity optomechanics, which explores the interactions between the circulating optical fields and the mechanical motion in an optomechanical resonator[2-4]. The optomechanical interactions take place via either the radiation pressure force induced by the optical fields or processes such as Brillouin scattering. These interactions can lead to quantum state transfer between relevant optical and mechanical systems and can also generate quantum entanglement between the optical and mechanical systems.

The main objective of this program has been to exploit the unique properties of an optomechanical system to develop light-matter interfaces that can map quantum states between two different optical wavelengths. In this final technical report, we summarize the key experimental and theoretical results obtained in this program. The experiment results include the demonstration of coherent inter-conversion between optical and mechanical excitations[5, 6], the realization of mechanically-mediated optical wavelength conversion via an optomechanical dark mode[7, 8], and the observation of Bogoliubov mechanical mode, a precursor for mechanical squeezing or entangled mechanical mode[9]. The theoretical results include the proposal and modeling of state swapping between optical and mechanical states and the development and

detailed analysis of a dark-mode-based approach for optical state transfer and also for the generation of optical entanglement[10-12]. In addition, we have also developed an approach that can return a mechanical system to its initial state after the completion of the relevant quantum operations[13]. This approach, which can be used for both optical state transfer and optical entanglement, resembles the Sorensen-Molmer mechanism for entanglement of trapped ions in a thermal environment[14, 15]. Overall, the advances achieved in this program laid the ground work for using optomechanical interfaces to enable quantum communication in a hybrid quantum network.

In addition to the main theme discussed above, we have also investigated the generation of mechanical squeezing via light-matter interactions. Squeezing is an important element in a hybrid quantum network for continuous variable systems. We show that mechanical squeezing well above the so-called 3dB limit can be achieved in the presence of strong thermal noise[16]. Another aspect in the quantum applications of optomechanics is the behavior of such systems in the single-photon limit, with ultra-strong coupling between the optical and the mechanical degrees of freedom. We have developed an appropriate theoretical approach to study the stochastic behavior of an optomechanical system in this limit[17].

2. SUMMARY OF KEY RESULTS

a) Coherent inter-conversion between optical and mechanical excitations

Theory By applying a strong, red-detuned pump pulse to an optomechanical system, we can linearize the radiation-pressure interaction between the optical and the mechanical mode and obtain an effective beam-splitter type of coupling in the form of

$$H_b = i\hbar\epsilon_i(a^\dagger b_i - b_i^\dagger a). \qquad (1)$$

After a duration of $\epsilon_i t = \pi/2$ for i=1, this pulse swaps the quantum state in the first optical mode with that in the mechanical mode. A similar pulse applied to the second optical mode can send the quantum state from the mechanical mode to the second optical mode[10]. In the limit of large cavity bandwidth ($\kappa > \varepsilon_i$), a quantum state can be transferred from the input port of the first optical mode to the output port of the second optical mode.

The thermal noise in the mechanical vibration presents a serious obstacle in achieving high-fidelity state transfer. To overcome this noise, we have designed a three-step scheme, in

which the thermal mechanical state is first swapped with an optical vacuum state. This precooling step can greatly reduce the thermal fluctuation in the system. The precooling step is then followed by the two swap gates as described in the previous paragraph[10].

Experiment As illustrated in Fig. 1, we used "writing" and "readout" pulses, which are one mechanical frequency, ω_m, below the optical cavity resonance, to realize state transfer between optical and motional states. In this experiment, the writing pulse converts a signal pulse at the cavity resonance to a coherent mechanical excitation. The readout pulse couples to the mechanical excitation at a later time, generating a retrieved optical pulse. The experiment was carried out in a silica microsphere with sphere diameter $D \sim 30$ μm (similar samples have been used in all the experiments presented in this report), mechanical damping rate $\gamma_m/2\pi = 20$ kHz, and cavity linewidth $\kappa/2\pi = 5$ MHz.

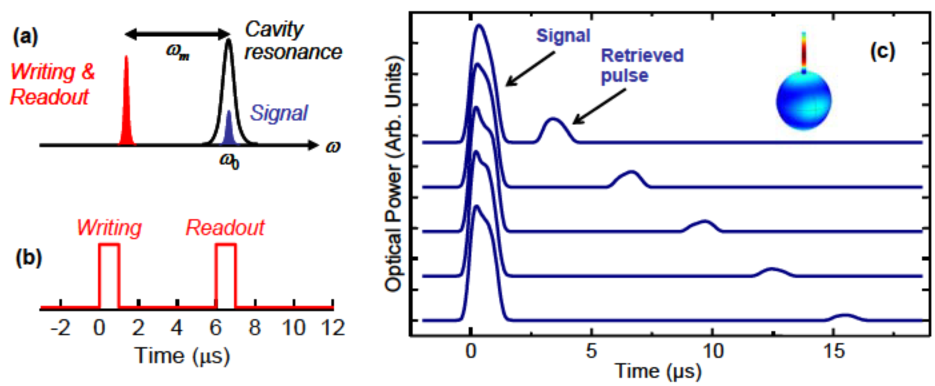


Fig. 1 State transfer between optical and motional states. (a) Spectral position of the writing, readout, and signal pulses. (b) Schematic of the pulse sequence. The signal pulse is synchronized with the writing pulse. (c) Optical emissions at the cavity resonance obtained as a function of time. From top to bottom, the delay between the writing and readout pulses are 3, 6, 9, 12, and 15 μs, respectively. The inset shows the spatial displacement pattern of the (1, 2) mechanical breathing mode used in the experiment.

Figure 1c shows optical emission powers at the cavity resonance obtained as a function of time and with increasing delay between the writing and readout pulses. The observation of the retrieved pulse shown in Fig. 1c demonstrates the inter-conversion between optical and motional states[5, 6]. The decrease of the retrieved pulse energy with increasing delay reflects the decay of the mechanical excitation. Additional experiments also showed that the conversion process is coherent.

Maximum efficiency of the state swapping between optical and motional states occurs when the optomechanical pulse area of the external driving field equals π. To demonstrate the π-

pulse, we modified slightly the experiment shown in Fig. 1 and used a 100 ns writing pulse to convert a 100 ns signal pulse into a mechanical excitation. The intensity of the mechanical excitation was measured with a weak and relatively long probe pulse arriving 1 μs after the writing pulse. Figure 2 shows the intensity of the mechanical excitation as a function of the optomechanical coupling rate, G. A π–pulse was obtained with $G/2\pi = 5$ MHz. The dashed line shows the corresponding theoretical calculation using the sample parameter, $\gamma_m/2\pi = 20$ kHz and $\kappa/2\pi = 10$ MHz.

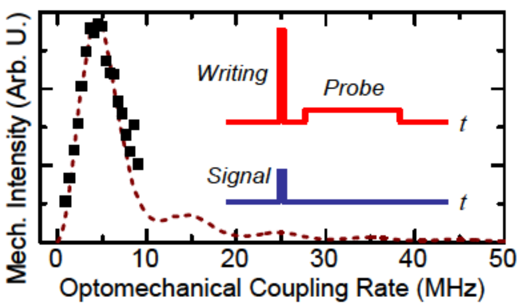


Fig. 2 Optomechanical π-pulse. The intensity of the mechanical excitation as a function of the estimated optomechanical coupling rate. Squares: experiments. Dashed line: theoretical calculations. Limited laser power prevents the observation of the damped Rabi oscillation. The inset shows a schematic of the pulse sequence used in the experiment. The duration of the writing and signal pulses is 100 ns.

b) Coherent optical wavelength conversion via optomechanical dark mode

Theory The double-swap scheme discussed above partially reduces the effect of thermal noise on the state conversion. To achieve better fidelity, we have explored the quantum state conversion via a mechanical dark mode. Here we consider two optical modes driven by respective red-detuned laser beams. The linearized Hamiltonian becomes

$$H = \sum_{i=1,2} -\hbar\Delta_i a_i^\dagger a_i + \hbar g_i (a_i^\dagger b_m + b_m^\dagger a_i) + \hbar\omega_m b_m^\dagger b_m, \qquad (2)$$

which describes a coupled three-mode system (see Fig. 3). This system has an eigenmode (ψ_1 in Fig. 3) that is decoupled from the mechanical mode. By transferring the quantum state via this dark mode, effects of the mechanical noise can be screened off the transferred state. Our calculation of the transfer fidelity on Gaussian states confirms this prediction (see Fug. 3)[11].

Meanwhile, we have also studied the transfer of a traveling photon state via this optomechanical interface. We show that the dark mode also plays an important role here. With the optimal condition, $g_1^2\kappa_2 = g_2^2\kappa_1$, only the dark mode is strongly excited by the incoming photon, and hence, the mechanical noise doesn't strongly degrade the transfer fidelity either[11].

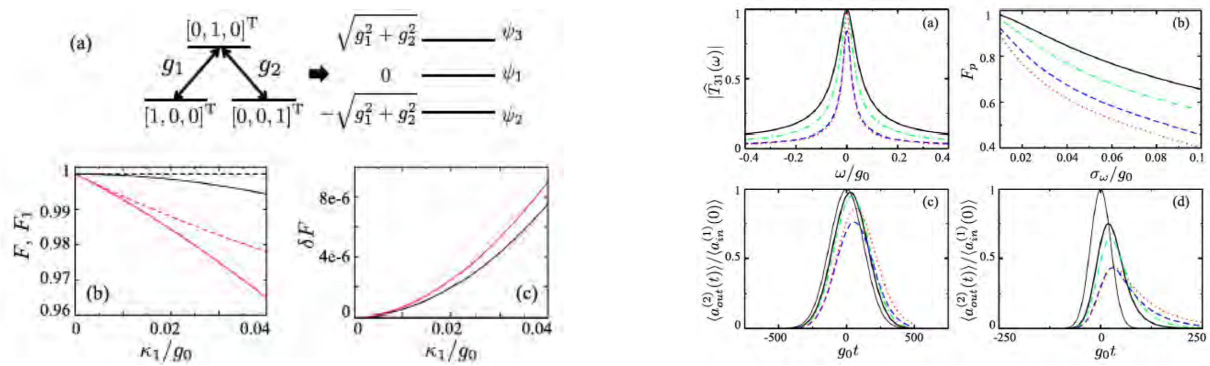


Fig. 3 Left: mechanical dark mode ψ_1 and transfer fidelity for selected Gaussian states. Right: transmission matrix element for traveling photons from the input port of one cavity to the output port of the other.

Experiment Mechanically-mediated optical wavelength conversion can take place via a dark mode that resembles the dark state in a Λ-type three-level system (see Fig. 4a). Figure 4b shows a schematic of two optical modes coupling to a mechanical oscillator. Two external driving fields, E_1 and E_2, which are ω_m below the respective cavity resonances, ω_1 and ω_2 (see Fig. 4c), can drive the optomechanical system into a dark mode. The formation of the dark mode, which is a special superposition of the two optical modes, necessitates the conversion of an input signal field, E_{in}, in one optical mode to an output field, E_{out}, in the other optical mode. Figure 4d shows a simplified schematic of the experiment, for which 8 μs long optical pulses were used.

Figure 4e shows transient, heterodyne-detected E_{out}. With E_{in} resonant with mode 1 (or mode 2), E_{out} is correspondingly resonant with mode 2 (or mode 1). The insets of Fig. 4e show that the heterodyne-detected signal features periodic oscillations with well-defined phase and with a frequency given by ω_m, demonstrating the coherent nature of the conversion process. Figure 4f plots the photon-conversion efficiency obtained from these experiments. The efficiency achieved (~10%) is limited by the modest optomechanical cooperativity (C_1 and C_2, for mode 1 and mode 2, respectively, are less than 5) and by the internal optical loss[7, 8].

We have demonstrated the formation of the dark mode by comparing directly emissions from the two optical modes[8]. Specifically, there are the two signatures for the dark mode excitation: i) the dark mode is decoupled from the mechanical system and thus features no optomechanically-induced transparency (OMIT). ii) The dark mode is a superposition of the two optical modes. The excitation of the dark mode leads to the coherent conversion of excitations between the two optical modes.

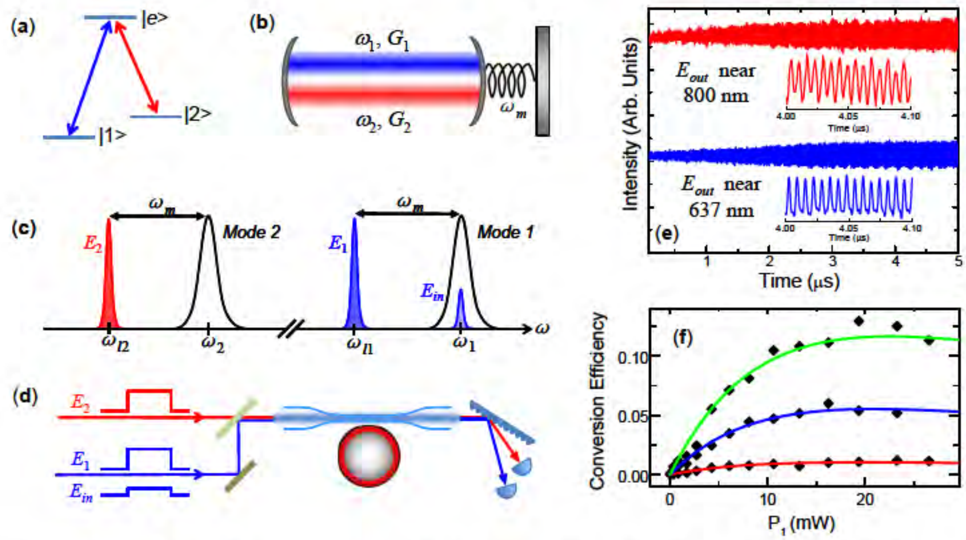


Fig. 4 Optical wavelength conversion. (a) A Λ-type three-level system. (b) A schematic of two optical modes coupling to a mechanical oscillator. (c) E_1 and E_2 drive the optomechanical coupling. (d) A simplified schematic of the experiment. (e) Heterodyne-detected E_{out}. Red: conversion from 637 to 800 nm. Blue: conversion from 800 to 637 nm. The insets show an expanded timescale. (f) Photon conversion efficiency. The signal field is converted from 800 to 637 nm, with input optical powers for E_{in}, E_1, and E_2 given by P_{in}=0.2 mW, P_1, and P_2=21, 11, and 2 mW (from top to bottom).

With the cooperativity for mode 1 fixed at C_1=1.4 and with increasing cooperativity for mode 2, C_2, Figs. 5a and 5b show diminishing OMIT contributions along with increasing conversion of the input signal field from mode 1 to mode 2 (see also Fig. 5c). Figure 5d shows that a dark mode fraction as high as 99% has been achieved in this experiment. Additional studies confirm the suppression of the mechanical excitation when the dark mode is formed[8].

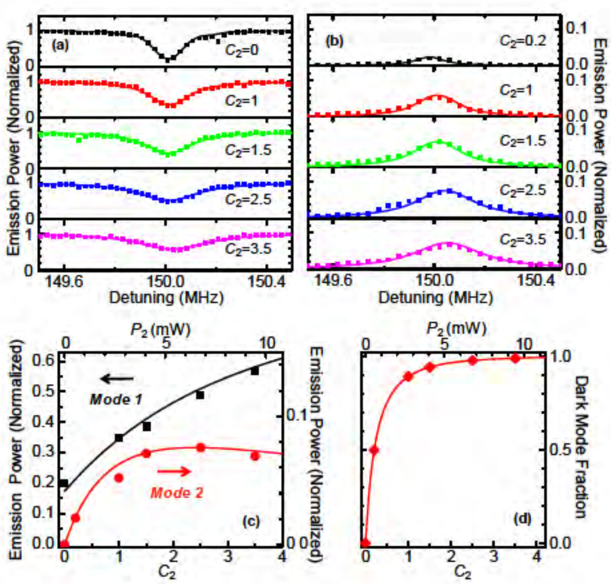


Fig. 5 Demonstration of the dark mode. (a), (b) Optical emissions from mode 1 and mode 2 vs detuning, $\Delta=\omega_{in}-\omega_{l1}$, with P_{in}=10 and 20 μW, respectively. C_1=1.4 (P_1=2.5 mW). The emission power from mode 1 is normalized to that obtained at the cavity resonance with $C_1=C_2=0$. The emission power from mode 2 is normalized to the input signal power. (c) Emission powers from mode 1 (squares) and mode 2 (circles) vs C_2, obtained at $\Delta=\omega_m$. Solid lines in (a), (b), and (c) are the results of the theoretical analysis. (d) Calculated dark mode fraction. The diamonds correspond to the experimental results plotted in (c).

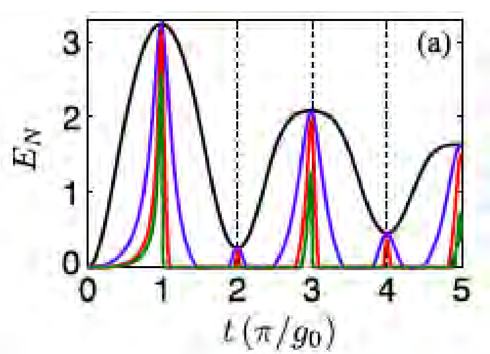
c) Entanglement generation via Bogoliubov dark mode (Theory)

Continuous variable entanglement is an indispensible resource in a hybrid quantum network. Generating entanglement between two cavity modes or their outputs via an optomechanical quantum interface is subject to the influence of mechanical noise, just as in the case of optical wavelength conversion discussed above. Using the idea of dark mode, we have developed a scheme to generate optical entanglement via the Bogoliubov dark mode, which is robust against the mechanical noise[12].

Applying red-detuned driving on cavity mode, a_1, and blue-detuned driving on cavity mode, a_2, we can write the resulting interaction Hamiltonian in the form

$$H_I = \hbar g_1(a_1^\dagger b_m + b_m^\dagger a_1) + i\hbar g_2(a_2^\dagger b_m^\dagger - a_2 b_m) \quad (3)$$

This Hamiltonian includes parametric-down-conversion type of coupling due to the blue-detuned drive. It can be shown that the system features a dark mode $\alpha_1 = -i\sinh(r)a_1 + \cosh(r)a_2^\dagger$ which does not contain the mechanical component, while the two other eigenmodes are bright modes that include the mechanical component. In this system, entanglement can be produced between all three modes due to their couplings. It can be shown that at stroboscopic time windows, the quantum interference between the bright modes cancels the contribution of the mechanical noise to the cavity state (see Fig. 6).



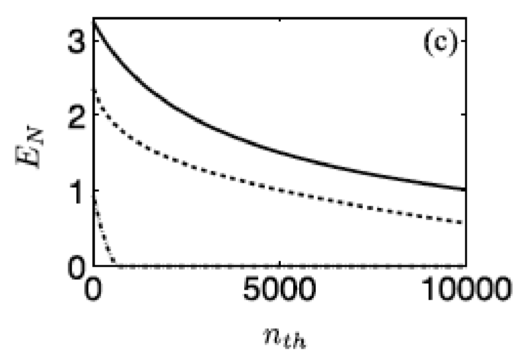


Fig. 6 Entanglement between cavity states in the time domain under constant driving parameters. Left: entanglement reaches peak values at stroboscopic time windows. Right: entanglement at selected time (peak value) versus thermal phonon number n_{th}.

Using the concept of Bogoliubov dark mode, high-fidelity entanglement can be generated between cavity outputs as well. In Fig.7, we plot the entanglement as a function of the output frequency relative to that of the cavity resonances. It can be seen that entanglement reaches peak

value at relative frequency ω=0, g_0,-g_0. However, as temperature increases, the entanglement at nonzero frequencies quickly decays as function of n_{th}; whereas the entanglement at ω=0 remains significant even at high temperature. We explain this effect using the evolution of the dark mode.

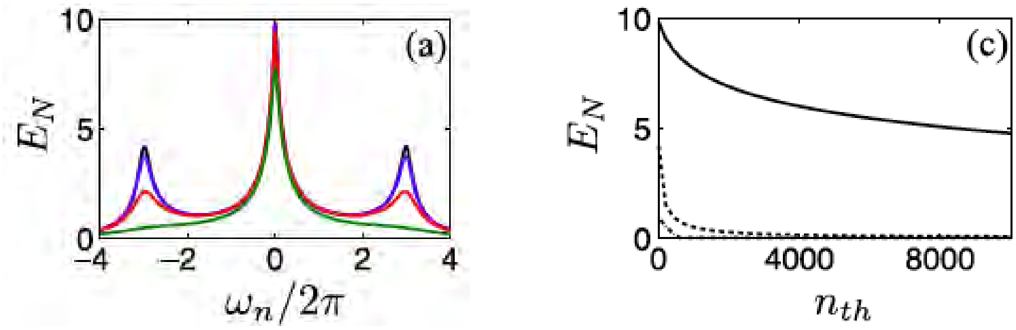


Fig. 7 Entanglement between cavity outputs in the frequency domain under constant driving parameters. Left: entanglement versus frequency. Right: entanglement at selected frequency (peak value) versus thermal phonon number n_{th}.

d) Experimental realization of Bogoliubov mechanical modes

To realize Bogoliubov mechanical modes, we have carried out experiments in a three mode optomechanical system, in which two radial breathing modes couple to an optical mode in a silica microsphere (see Figs. 8a-8c). For the experiment, a beam-splitter like process was driven by a laser field at the red sideband and a parametric-down-conversion process was driven by a laser at the blue sideband. The combined red and blue sideband coupling can lead to the generation of phonon pairs as well as the formation of Bogoliubov mechanical modes that have the mathematical form of two-mode squeezed states.

The Bogoliubov mode features a characteristic optomechanical coupling rate given by $G=\sqrt{G_1^2-G_2^2}$ (G_1 and G_2 are the respective red and blue sideband coupling rates), which can be directly probed with the technique of OMIT. The experimental results shown in Figs. 8d and 8e show the expected competition between the red and blue sideband coupling[9]. The periodic modulations in these data are due to the relatively short pulse duration (7 μs) used in the experiments. The solid lines show good agreement between the experiment and theory. In the limit that $G_2 > G_1$, optomechanically induced gain is observed. In this regime, the Bogoliubov mode can be driven above the threshold for parametric instability. Additional experimental studies further show that the resulting self-induced mechanical oscillations reflect the underlying process of the phonon pair generation[9].

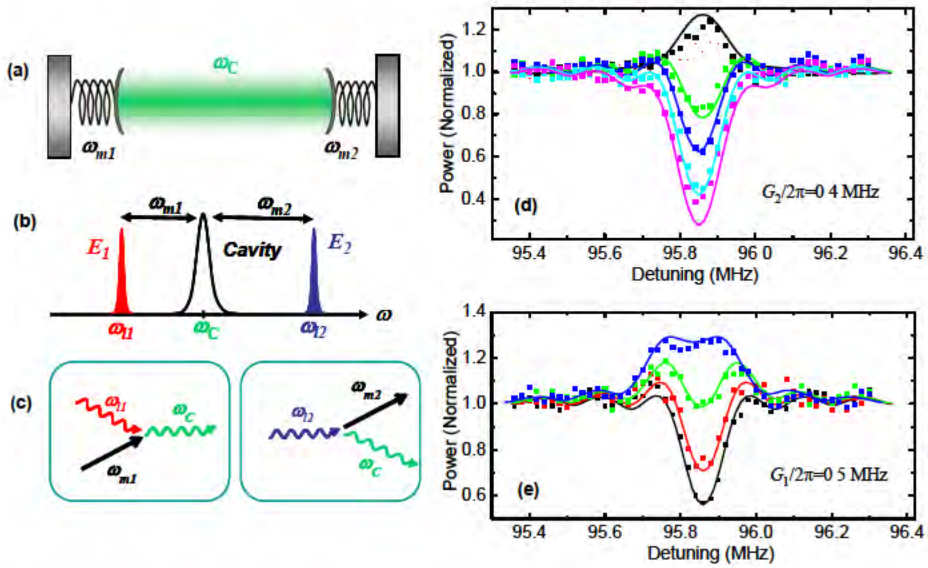


Fig. 8 (a) Schematic of two mechanical modes coupling to an optical mode. (b) Two optical driving fields, E_{l1} and E_{l2}, at the red and blue sideband, respectively, couple to the respective mechanical mode. (c) Diagram for the red (left) and blue (right) sideband coupling, illustrating the processes of phonon-photon inter-conversion and phonon-photon pair generation. (d) and (e) OMIT responses of the Bogoliubov mode (the optical emission vs the detuning between a signal and E_1). From top to bottom: $G_1/2\pi$=0.23, 0.43, 0.5, 0.61, 0.72 MHz for (d); $G_2/2\pi$=0.65, 0.58, 0.49, 0.40 MHz for (e).

e) Sorensen-Molmer scheme for generating optical entanglement

This work is motivated by earlier theoretical and experimental studies on entangling trapped ions in a thermal environment. In these studies, the entanglement operation takes place via the mechanical degrees of freedom of the ions. Robust entanglement can be achieved in a thermal environment with a class of Hamiltonian that returns the motion of the ions to their initial state upon the completion of the entanglement operation[14, 15]. We have analyzed a pulsed entanglement process using an optomechanical interaction Hamiltonian that has the features of the Sorensen-Molmer mechanism and returns the mechanical system to its initial state upon the completion of the entanglement process. Our theoretical analysis shows that we can extend the Sorensen-Molmer approach to an optomechanical system[13]. In particular, significant optical entanglement can be generated in the weak coupling regime, even in the presence of a large thermal phonon occupation n_{th}~10^3.

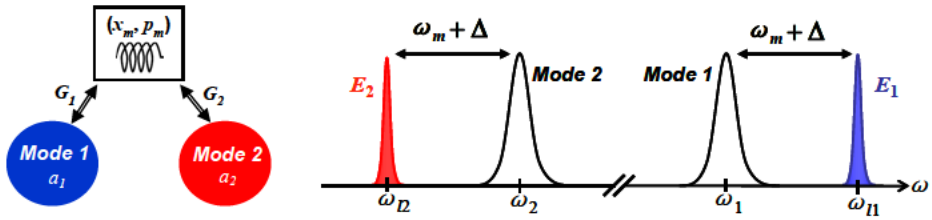


Fig. 9 Schematic of a three-mode optomechanical system for the generation of optical entanglement, with the two driving fields, E_1 and E_2, slightly detuned from the respective sideband resonance.

For the three-mode optomechanical system shown in Fig. 9, the two driving fields are slightly detuned from the respective sideband resonance with equal detuning Δ, but still maintain the overall two-photon resonance, $\omega_{l1} + \omega_{l2} = \omega_1 + \omega_2$. We assume that the system is in the resolved sideband regime, with $\omega_m >> \kappa_{1,2} >> \gamma_m$ and $\omega_m >> G_{1,2}$, where $\kappa_{1,2}$ are the cavity decay rates, γ_m is the mechanical damping rates, $G_{1,2}$ are the multi-photon optomechanical coupling rates. The optomechanical interaction Hamiltonian in a rotating frame is given by,

$$H_{\text{int}} = (G_1 \hat{a}_1 + G_2 \hat{a}_2^+) \hat{b} e^{-i\Delta t} + H.c. \tag{4}$$

With dimensionless quadrature variables defined as $\hat{x}_i = (\hat{a}_i + \hat{a}_i^+)/\sqrt{2}$ and $\hat{p}_i = i(\hat{a}_i^+ - \hat{a}_i)/\sqrt{2}$ (i=1, 2), $\hat{x} = \hat{x}_1 + \hat{x}_2$, $\hat{p} = \hat{p}_2 - \hat{p}_1$, $\hat{x}_m = (\hat{b} + \hat{b}^+)/\sqrt{2}$, and $\hat{p}_m = i(\hat{b}^+ - \hat{b})/\sqrt{2}$, we rewrite H_{int} in the form,

$$H_{\text{int}} = f_1(\hat{x}, \hat{p}, t)\hat{x}_m + f_2(\hat{x}, \hat{p}, t)\hat{p}_m . \tag{5}$$

The exact propagator of this system is then given by

$$U(t) = \exp[-iA(\hat{x}, \hat{p}, t)] \cdot \exp[-iF_1(\hat{x}, \hat{p}, t)\hat{x}_m] \cdot \exp[-iF_2(\hat{x}, \hat{p}, t)\hat{p}_m] . \tag{6}$$

At regularly spaced time interval $t_n = 2\pi n / |\Delta|$ (n= 1, 2, 3…), $F_1(\hat{x}, \hat{p}, t_n) = F_2(\hat{x}, \hat{p}, t_n) = 0$, returning the mechanical system to its initial state. At the same time, we have

$$U(t_n) = \exp[-iA(\hat{x}, \hat{p}, t_n)], \text{ with } A(\hat{x}, \hat{p}, t_n) = -\frac{G^2}{2|\Delta|}(\hat{x}^2 + \hat{p}^2) t_n , \tag{7}$$

which generates entanglement between the two optical modes (or two-mode squeezed states), with the squeezing parameter given by $r = G^2 t_n / (2|\Delta|)$. A sideband detuning that is less than G can lead to a large squeezing parameter at $t_1 = 2\pi / |\Delta|$. To maintain thermal robustness in the presence of damping, the detuning needs to far exceed the thermal decoherence rate, $|\Delta| >> n_{th}\gamma_m$.

Figure 10 shows the entanglement (log negativity, E_N) between relevant discrete modes in the output of the cavity as a function of the pulse duration, with $\kappa_1=\kappa_2=6\text{x}10^3\gamma_m$ and $\Delta/\kappa_1=1/6$ and with various thermal phonon occupation. For $G_1=G_2=\kappa_1/3$, E_N oscillates with the pulse duration, with the entanglement maxima occurring at pulse durations satisfying the condition, $t_n=2\pi n/|\Delta|$. With increasing thermal phonon occupation, the maxima decrease gradually, while the minima quickly approach zero. Significant entanglement can still be achieved with a thermal phonon occupation $n_{th}\sim10^3$.

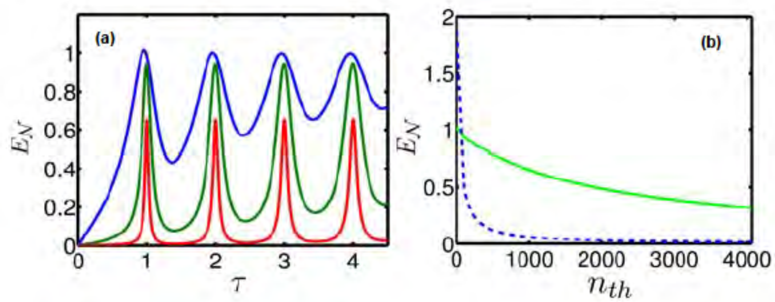


Fig. 10 (a) Entanglement in the output of the cavity in the bad cavity limit. From top to bottom: $n_{th}=10$, 10^2, 10^3. τ has units of $2\pi/\Delta$. (b) Maximum entanglement generated as a function of n_{th}. Solid line: $G_1=G_2$. Dashed line: $G_1=0.3\kappa_1$, $G_2=\kappa_1/3$.

f) Mechanical squeezing robust against thermal noise

Quantum squeezing of mechanical modes is one of the key macroscopic quantum effects that can be utilized to study the quantum-to-classical transition and to improve the precision of quantum measurements. However, strong mechanical squeezing that could beat the effect of noise has never been generated. We have explored a method to generate strong steady-state mechanical squeezing in an optomechanical system via mechanical nonlinearity and cavity cooling. The mechanical nonlinearity required in this scheme is achieved by coupling the mechanical mode to an ancilla system, such as an external electrode or a qubit, and its magnitude far exceeds that of the intrinsic mechanical nonlinearity (see Fig. 11) [16].

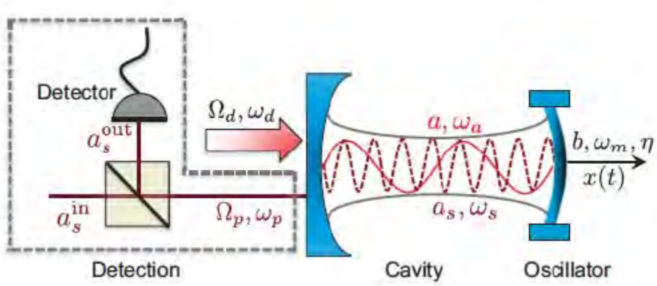


Fig. 11 Schematic setup for generation of mechanical squeezing. Mechanical mode couples to a nonlinear element. Cavity driven by a red-detuned source with frequency ω_d.

The driving on the cavity is a red-detuned monochromatic source which generates strong optomechanical coupling between the cavity and the mechanical modes and greatly reduces the thermal fluctuations of the mechanical mode. This driving, when combined with the nonlinearity of the mechanical mode, also induces a parametric-amplification process which plays a key role in generating squeezing. We show that in the vicinity of the steady state, the system has an effective Hamiltonian

$$
\begin{aligned}
H_{\text{eff}} = {} & \Delta_a a^\dagger a + \tilde{\omega}_m b^\dagger b + \Lambda(b^2 + b^{\dagger 2}) \\
& - G(a + a^\dagger)(b + b^\dagger),
\end{aligned}
\tag{8}
$$

which includes both a parametric amplification term and a cavity cooling term. Furthermore, we find that in a rotated frame, the physical process can be exactly mapped to a cooling equation where the mechanical noise is extracted away from the system. In the physical (original) frame, we then achieve strong squeezing that is robust against the thermal noise. Optimal squeezing occurs when the detuning of the cavity driving is equal to the mechanical frequency in the rotated frame (see Fig. 12).

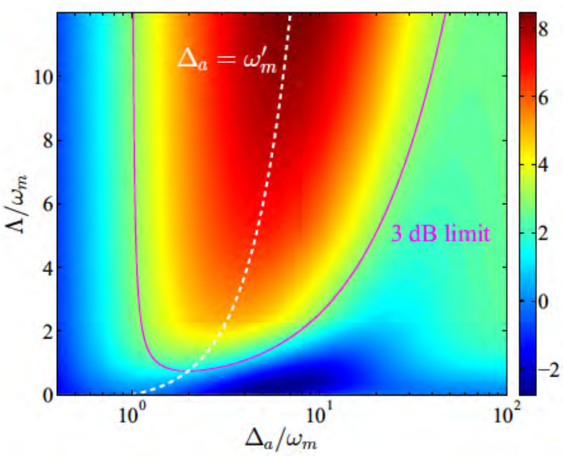


Fig. 12 The squeezing of X (in units of dB) versus detuning and coupling Λ. The white dashed line indicates the position of optimal squeezing.

3. OUTLOOK

Mechanical degrees of freedom, which have often been overlooked in studies of quantum systems, have emerged as a promising platform for interfacing disparate quantum systems. The ubiquitous nature of mechanical motion can enable a mechanical oscillator to couple to nearly any type of quantum systems, including charge, spin, atomic, and superconducting qubits, as well as to photons at nearly any wavelength. Considerable experimental progresses have already been made in optomechanical and also electromechanical systems. Mechanically-mediated

optical wavelength conversion, including that between optical and microwave fields, have been successfully demonstrated in a classical regime. With further advance in the design and engineering of optomechanical resonators, near unity conversion efficiency is achievable.

A key technical challenge for using mechanical degrees of freedom in applications such as quantum information processing is to overcome the detrimental effects of thermal motion inherent in a mechanical system. For the mechanically-mediated quantum state transfer between optical fields, a conceptually straightforward approach is a double swap, converting the field in the first optical mode to a mechanical excitation, followed by the conversion of the mechanical excitation to an field in the second optical mode. The double swap process, however, is strongly affected by thermal phonons. A brute force approach to avoid this complication is to cool the mechanical system to its motional ground state. Two different, but closely related, approaches can, however, enable mechanically-mediated quantum state transfer even in the presence of thermal phonons. The dark mode approach is based on the adiabatic passage of a dark mode and is analogous to the Stimulated Raman adiabatic passage (STIRAP) of dark states in an atomic system. The Sorensen-Molmer approach returns the mechanical system to its initial state after the completion of the relevant quantum operation, which resembles the Sorensen-Molmer mechanism for entanglement of trapped ions in a thermal environment. Both approaches aim to take advantage of mechanical degrees of freedom, while avoiding the detrimental effects of thermal environment during the state transfer process. For the dark mode approach, the mechanical oscillator still needs to be precooled to its motional ground state, since perfect adiabatic limit can never be attained for realistic experimental parameters[18, 19]. Precooling to the ground state, however, is not required for the Sorensen-Molmer approach. Thus far, neither adiabatic passage of the dark mode nor the Sorensen-Molmer mechanism has been realized experimentally in an optomechanical system.

Results from our as well as other groups in the DARPA ORCHID program show that optomechanical interfaces can generate or lead to all necessary elements in a hybrid quantum network for the purpose of quantum information transfer. Future experimental and theoretical efforts will likely focus on demonstrating quantum state transfer at the single-photon level, on overcoming thermal mechanical noise at elevated temperatures, and also on generating and characterizing optical as well as mechanical entanglement.

4. PUBLICATION

4.1 Peer reviewed

1) Chunhua Dong, Victor Fiore, Mark C. Kuzyk, Lin Tian, and Hailin Wang, "*Optical wavelength conversion via optomechanical coupling in a silica resonator*," Annalen der Physik 527, **100** (2015).

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4.2 Reviews and News

1) L. Tian, ``Viewpoint: Cool and Heavy'', Physics **8**, 8 (2015).

5. SCIENTIFIC PERSONNEL

Victor Fiore (graduate student, U Oregon)
Mark Kuzyk (graduate student, U Oregon)
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Hailin Wang (PI)

Victor Fiore graduated with PhD in physics in May 2015. (U Oregon)
Mark Kuzyk and Thein Oo are expected to graduate in the summer of 2016. (U Oregon)
Dan Hu graduated with Ph.D. in Physics in Jan. 2015 (UC Merced).

6. REPORT OF INVENTIONS

No patents were filed.

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Abstract

An optomechan ca resonator features the un que property that an opt ca y act ve mechan ca mode can coup e to any of the opt ca resonances n the resonator v a rad at on pressure. The ma n object ve of th s program s to exp o t th s un que property to deve op a   ght-matter nterface that can map quantum states between two d fferent opt ca wave engths. Us ng s   ca m crospheres as a mode optomechan ca system, these stud es have ed to the exper menta rea zat on of coherent nter-convers on between opt ca and mechan ca exc tat ons and to the demonstrat on of mechan ca y-med ated coherent convers on between two opt ca modes. In add t on, Bogo ubov mechan ca mode, wh ch s a precursor for entang ed mechan ca mode, has a so been rea zed n a system, n wh ch two mechan ca modes coup e a common opt ca mode v a respect ve red and b ue s deband coup ng.

A part cu ar emphas s of th s program s on overcom ng the effects of the therma mechan ca mot on n mechan ca y-med ated opt ca state transfer or opt ca entang ement. Two d fferent approaches have been proposed and ana yzed theoret ca y. One approach exp o ts mechan ca y-dark opt ca super modes. These dark modes can enab e the opt ca mode convers on or opt ca entang ement generat on w thout exc t ng the mechan ca system, thus avo d ng the effects of the therma mechan ca mot on. Deta ed exper menta stud es show that opt ca mode convers on demonstrated ndeed took p ace v a the dark

mode. Another approach returns the mechan ca system to ts n t a state after the comp et on of the re evant quantum operat ons. Th s approach resemb es the Sorensen-Mo mer mechan sm for entang ement of trapped ons n a therma env ronment. Both approaches a m to take advantage of mechan ca degrees of freedom, wh e avo d ng the detr menta effects of therma mechan ca mot on.

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